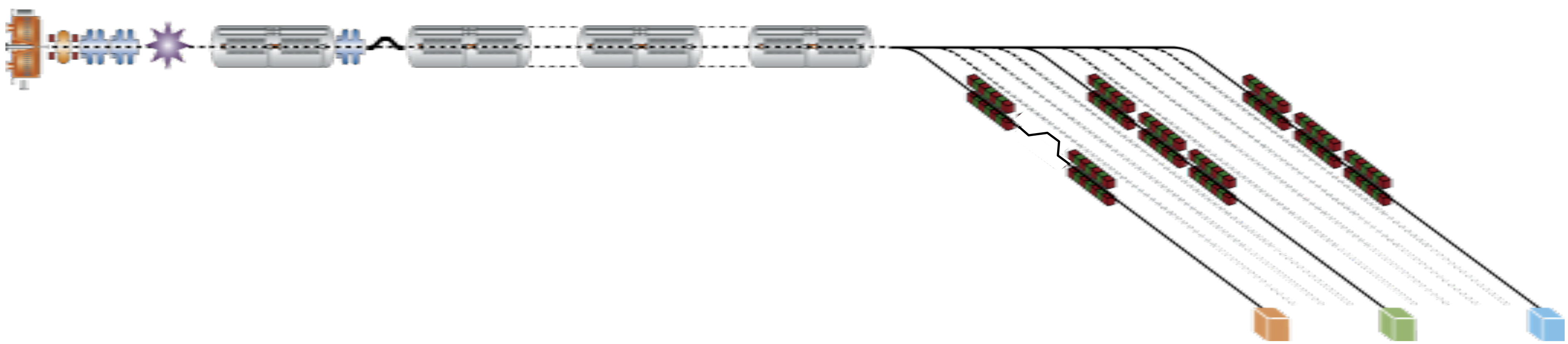
Vision for a Next Generation Light Source Facility



John Corlett
For the Next Generation Light Source Team
Laser Safety Officer Workshop
July 29, 2010

Choices We've Made in Design Studies for a Next Generation Light Source (NGLS)

- **A coherent soft x-ray source addresses scientific needs**
  - **Requires short wavelength light with high peak and average brightness, high repetition rate, ultrashort pulses, and high energy resolution**

- **Utilizing laser control of relativistic electron beams is enabling**
  - **Allows optimal control of x-ray source characteristics**

- **Technical choices are driven by user needs**
  - **Photoinjector, superconducting accelerator, charge per bunch, electron energy, seeding, repetition rate, spectral range, multiple beamlines**

The Technology of a Next Generation Light Source

Developments in high brightness electron beams, lasers, seeding, and optical manipulations allow enhancement of performance of Free Electron Lasers

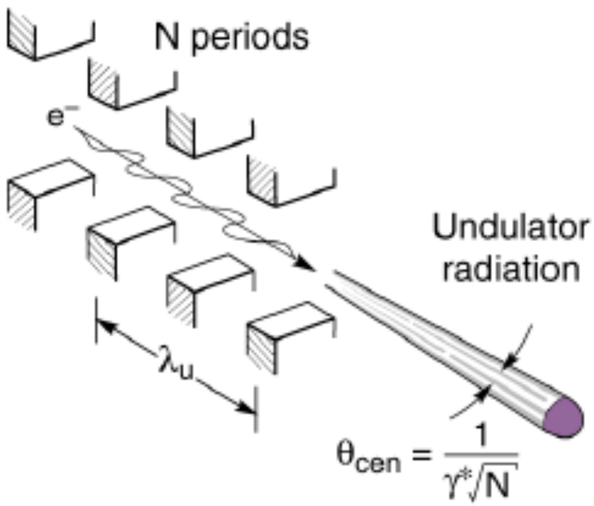
- **Intense X-ray pulses from VUV to hard X-ray**
- **Control of pulse duration**
- **Control of pulse energy**
- **Spatial coherence**
- **Temporal coherence**
- **Generation of shorter wavelengths in harmonic stages**
- **Precise synchronization**
- **Shorter undulators**
- **THz–IR pump pulse**

***PLUS* a superconducting accelerator and high repetition rate injector allows high-power electron and photon beams**

- **High repetition rate X-ray pulses**
- **CW pulse structure**
- **High average power X-ray beams**

BERKELEY LAB

Electron Beam "Wiggles" and Radiation Builds in a Resonant Process



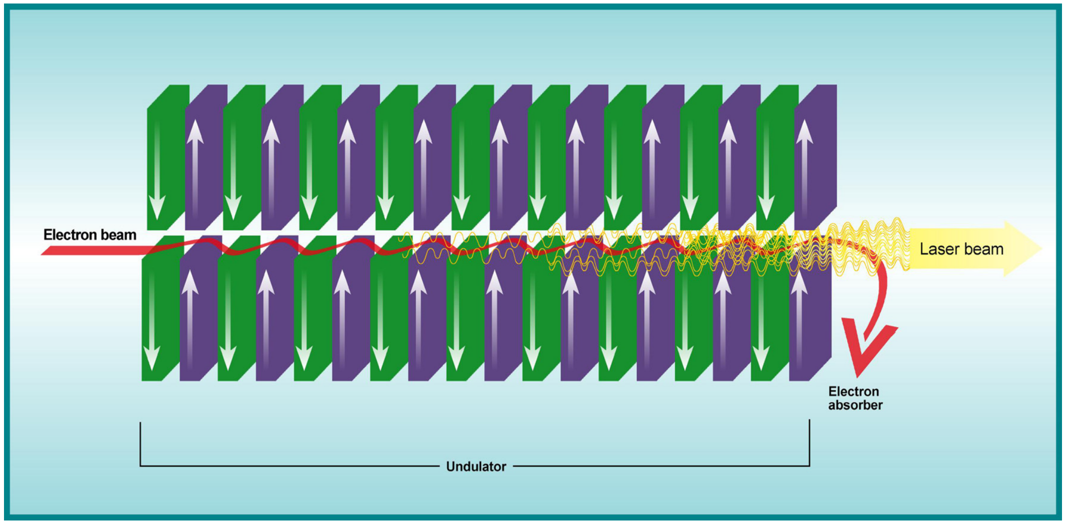
Undulator period

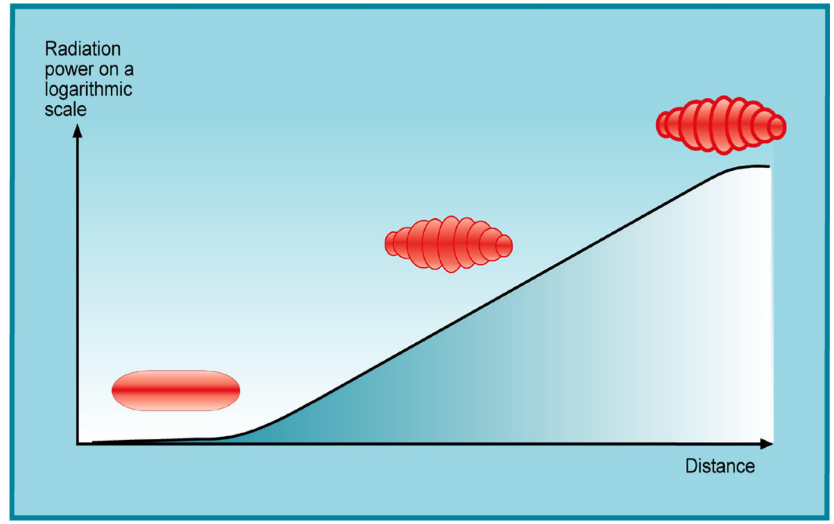
X-ray wavelength **Undulator parameter**

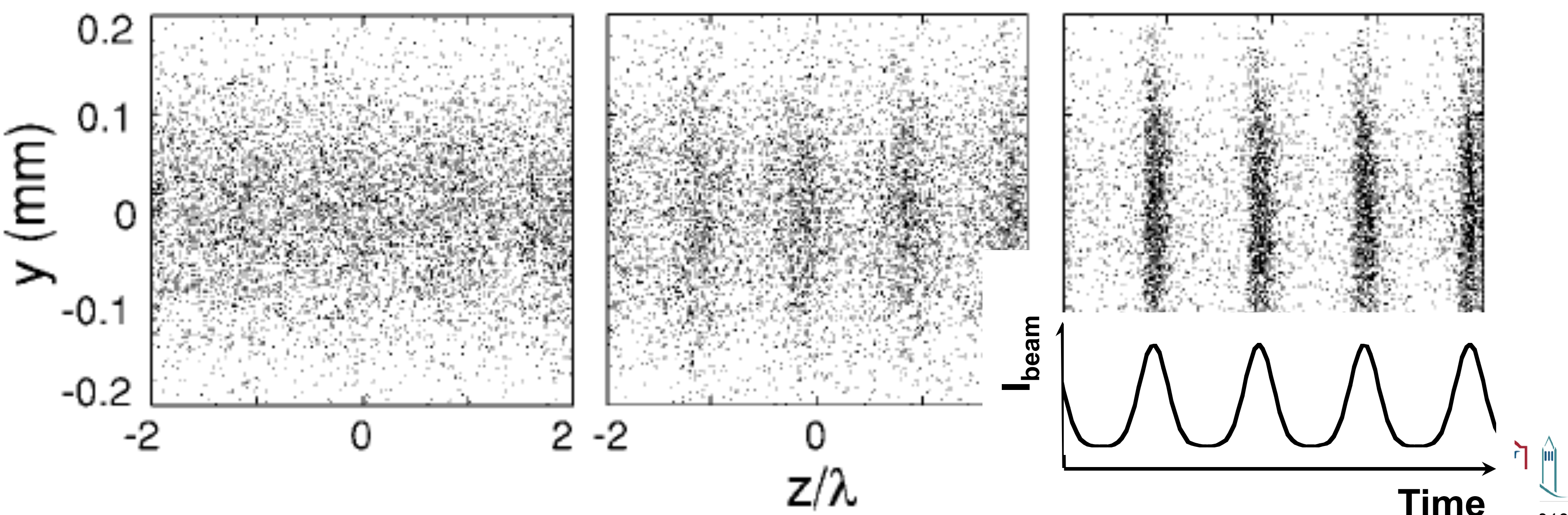
$$\lambda_{x-ray} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

- **Over one undulator period, the electron is delayed with respect to the light by one optical wavelength**

Microbunching Introduces *Coherent* Emission in a Free Electron Laser





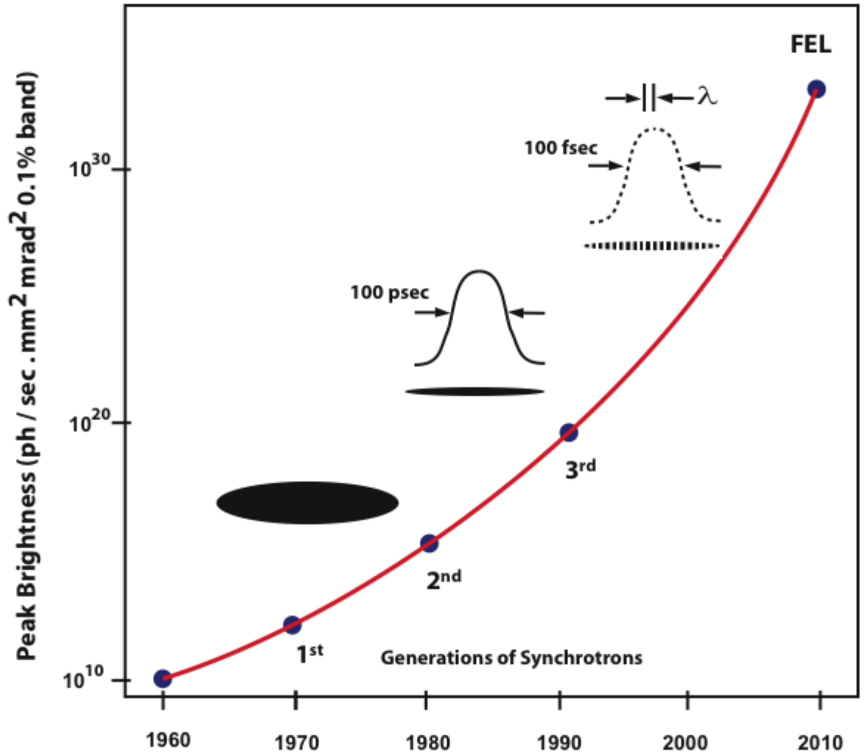


Coherent emission - higher flux and brightness

Dominates if s_z < l

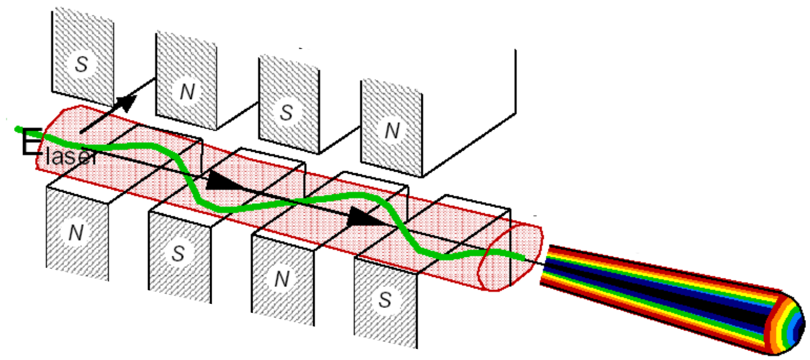
$$I_{total}(\omega) = \left\{ N + N(N-1)\left|g(k)\right|^2 \right\} I_e(\omega)$$

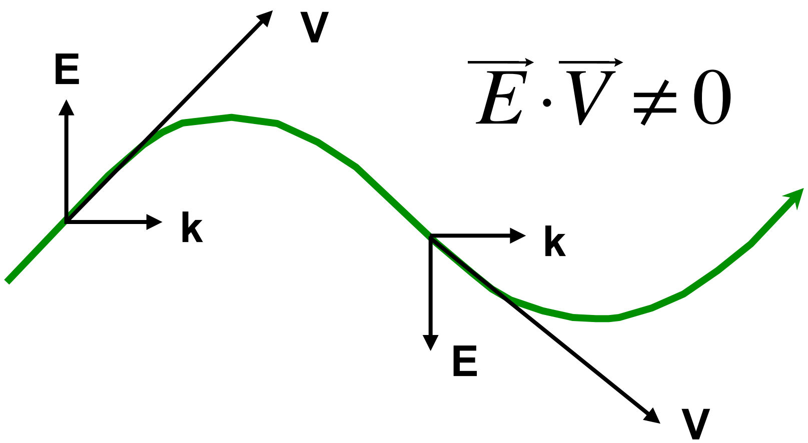
$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz}\, dz$$



Incoherent

Laser Manipulations of the Electron Beam





$$\vec{E}\cdot\vec{V}\neq 0$$

Wiggler period

Undulator parameter

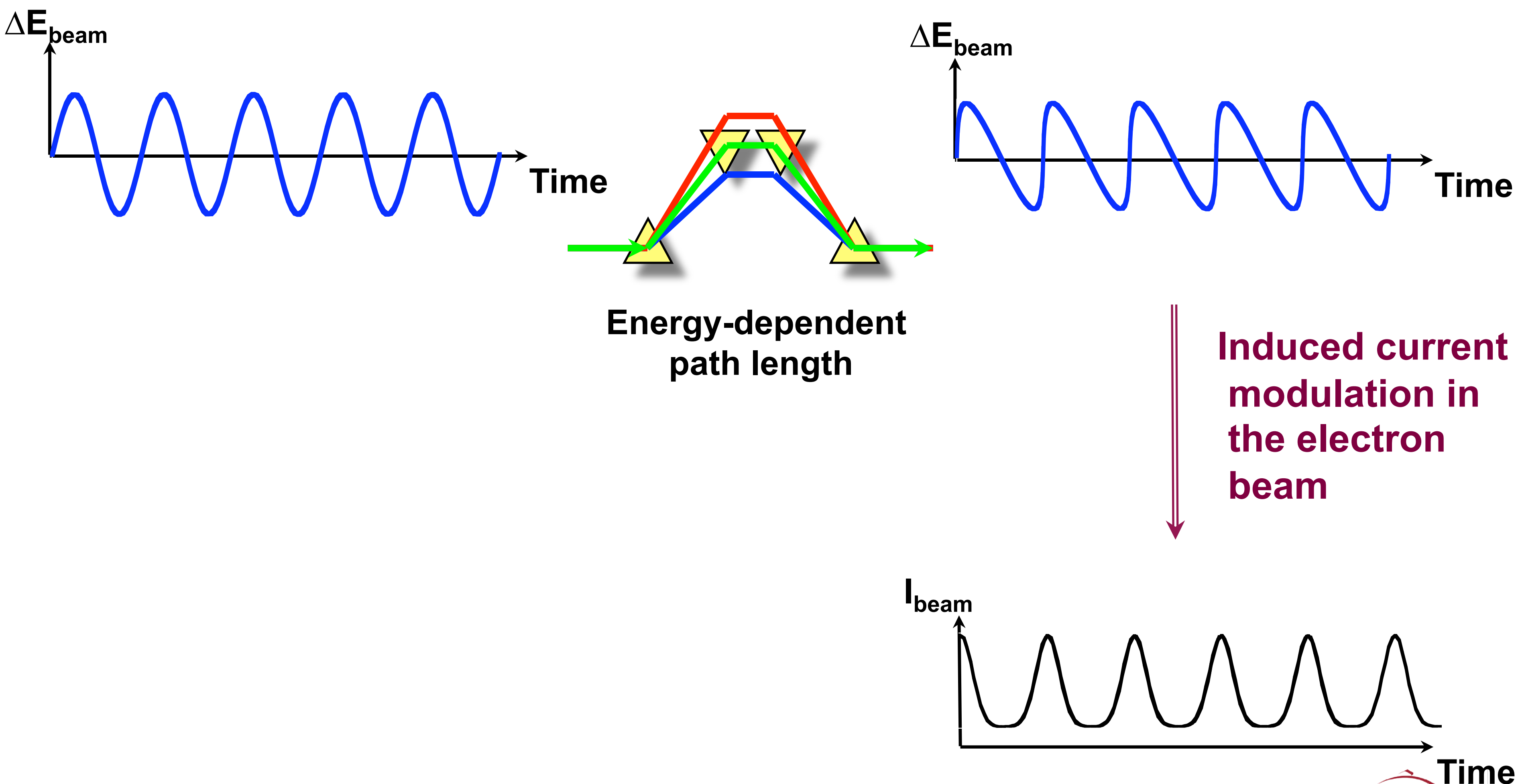
$$\lambda_w = 2\gamma^2\lambda_L/(1+\frac{K^2}{2})$$

Laser wavelength

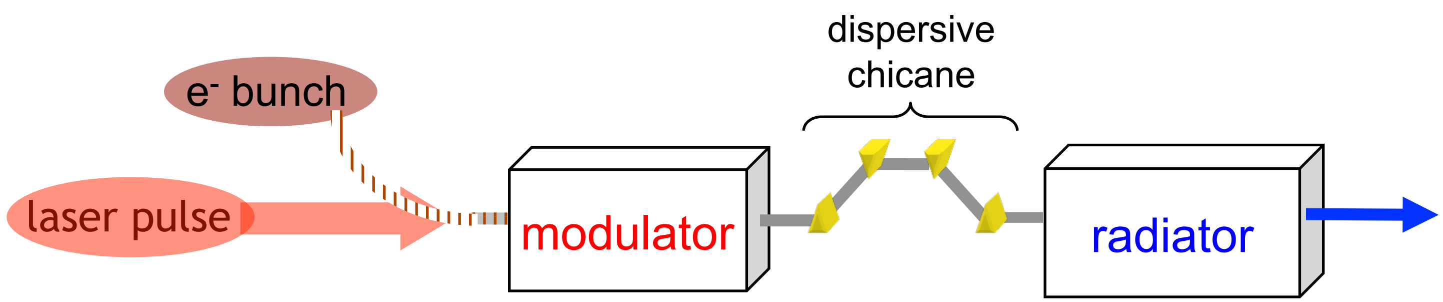
- **Electron beam couples to E-field of laser when co-propagating in an undulator**
- **Over one undulator period, the electron is delayed with respect to the light by one optical wavelength**

Bunching of the Electron Beam

ENERGY MODULATION FOLLOWED BY DISPERSIVE SECTION



High Gain Harmonic Generation (HGHG)



$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

n ~ a few-several

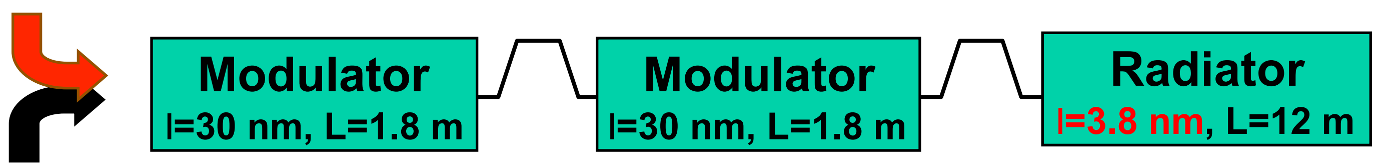
L.-H. Yu et al, Science 289 932-934 (2000)

HHG Seeded FEL

Example with seed at 30 nm, radiating in the water window
First stages amplify low-power seed

100 kW
l=30 nm

1 GeV beam
500 A
1.2 micron emittance
75 keV energy spread



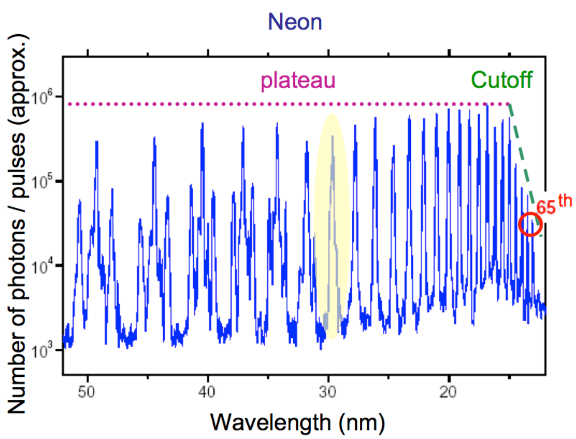
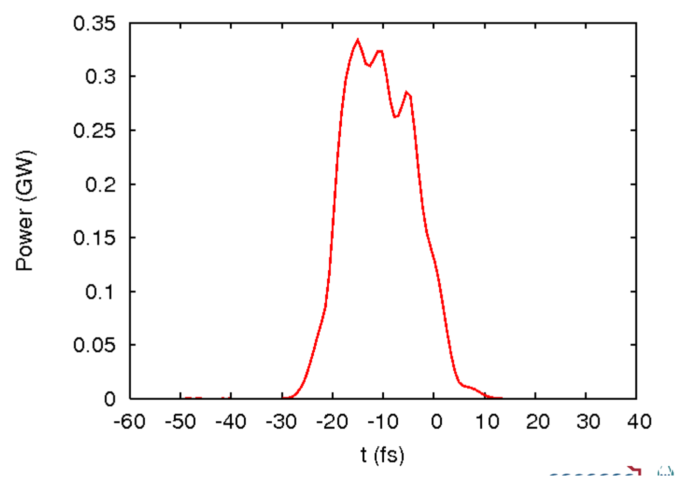


Fig. 1: High Harmonic spectrum in Ne.

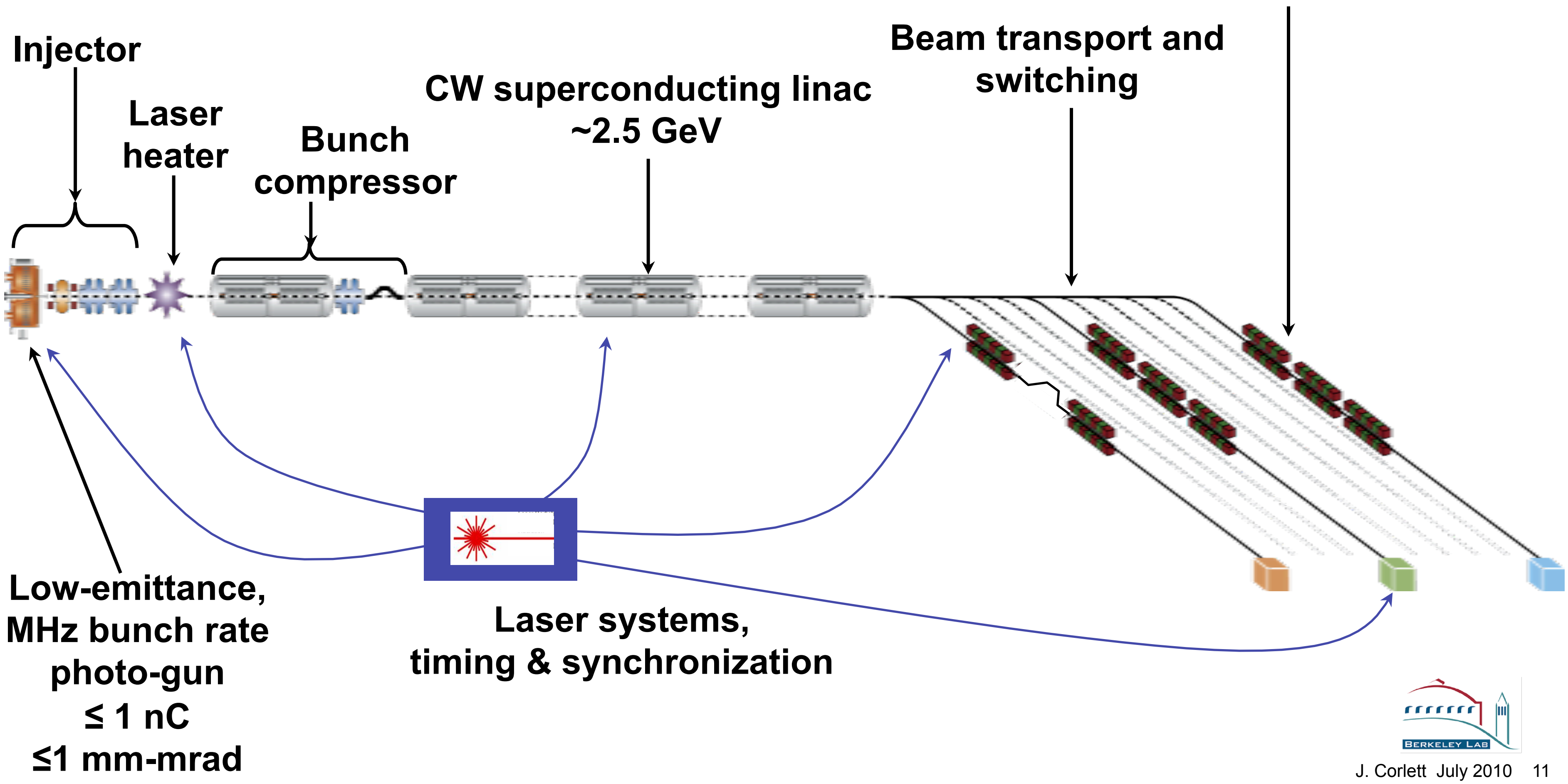
300 MW output at 3.8 nm (8^{th} harmonic) from a 25 fs FWHM seed



M. Gullans, G. Penn, and A.A. Zholents, “Performance study of a soft X-ray harmonic generation FEL seeded with an EUV laser pulse”, *Optics Communications* 274, 167-175 (2007)

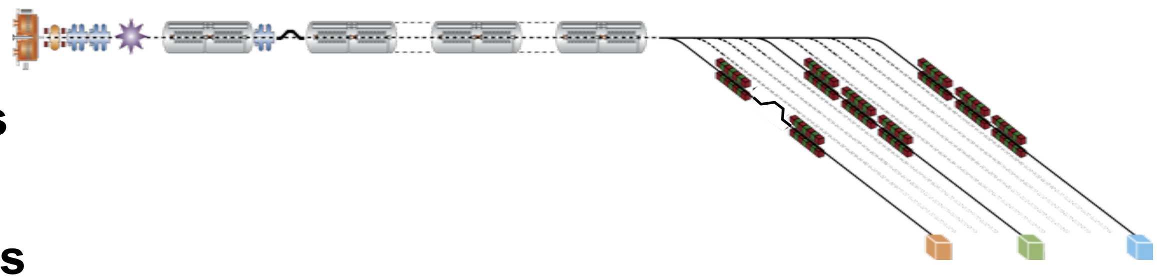
Concept for a High-Repetition Rate, Seeded, VUV–Soft X-ray FEL Facility

Array of 10 configurable FEL beamlines, up to 20 X-ray beamlines
100 kHz CW pulse rate, capability of one FEL having MHz rate
- Independent control of wavelength, pulse duration, polarization
- Each FEL configured for experimental requirements;
  - seeded, attosecond, ESASE, mode-locked, echo effect, etc



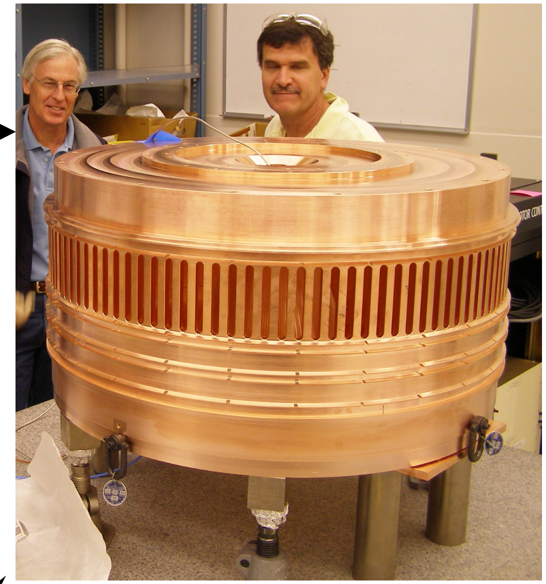
NGLS Design Concept

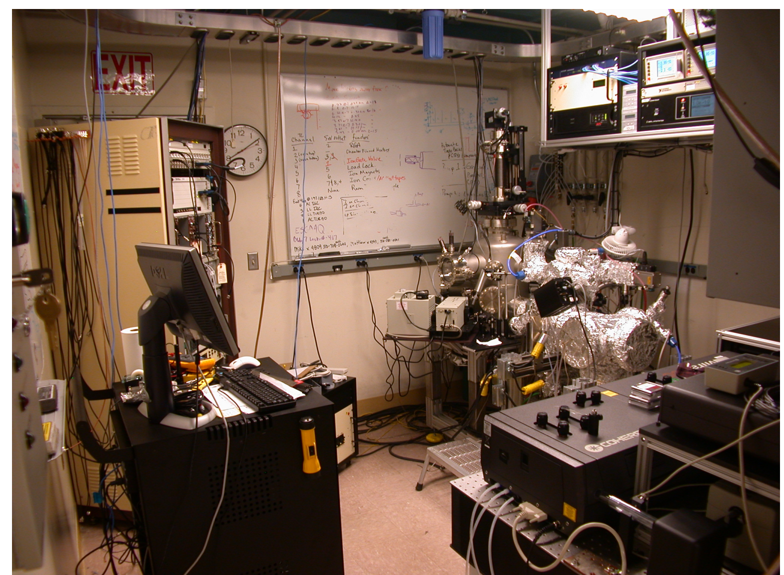
- Coherent soft x-ray laser
- 10 eV - 1 keV range
  - harmonics to 5 keV
- Seeded by optical lasers
- Multiple, simultaneous beams
  - with different properties
- Time-bandwidth limited pulses
  - Ultrashort (~250 attoseconds)
  - Narrow bandwidth (meV)
- High peak power - for nonlinear optics (~ 1 GW)
- Control of peak power - 10–1000 MW to minimize sample damage
- High average power - for low scattering rate experiments (~ 1–10+ W)
- High repetition rate - for good S/N (~100 kHz–MHz+ for some beamlines)
- Capable of serving large number of users (~ 2000 users/year)



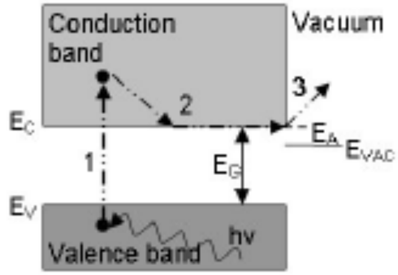
Current R&D Activities

- **R&D in critical technologies**
  - **CW VHF photo-gun**
  - **High efficiency photocathodes**
  - **Fast kicker and pulser**
  - **Laser development (SBIR and LLNL collaboration)**
  - **Short-period undulator R&D**
  - **Timing & synchronization systems**



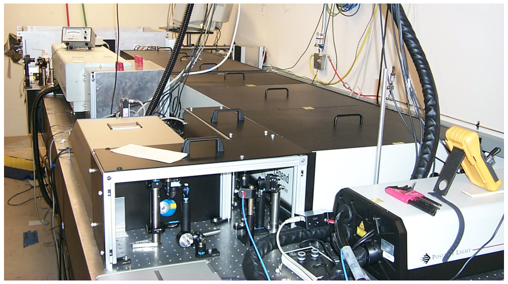


A High Rep-rate Injector

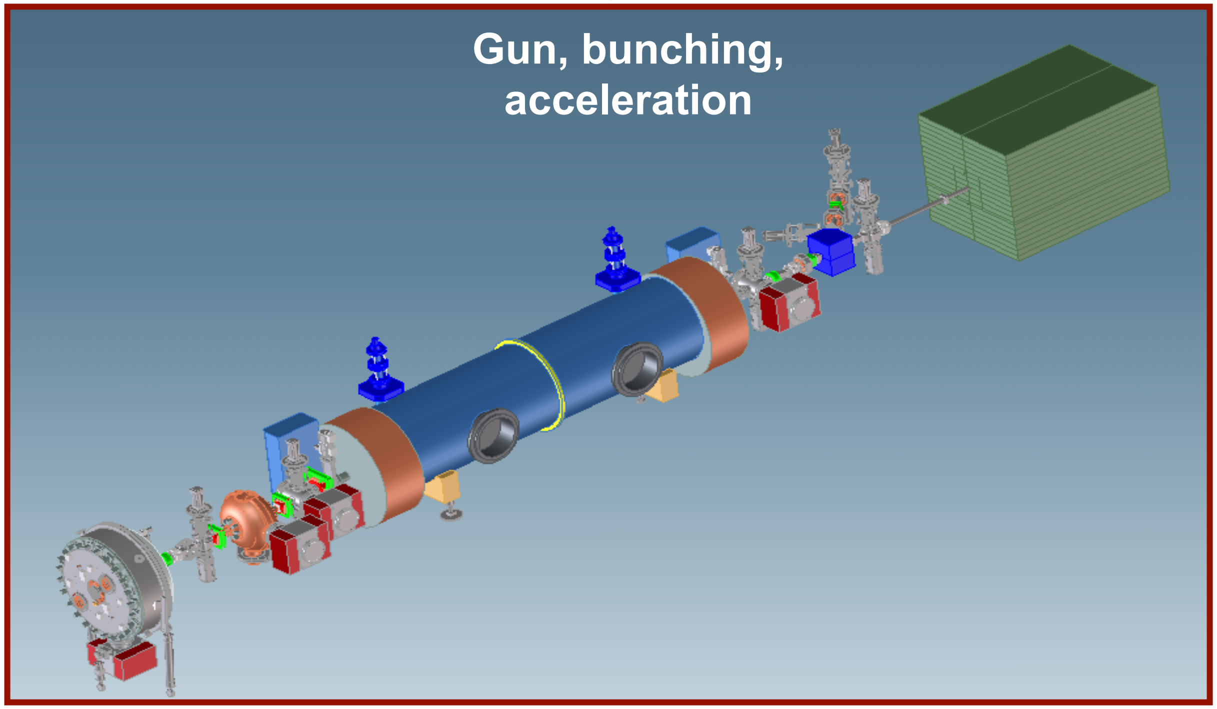


Low emittance, high quantum efficiency cathodes

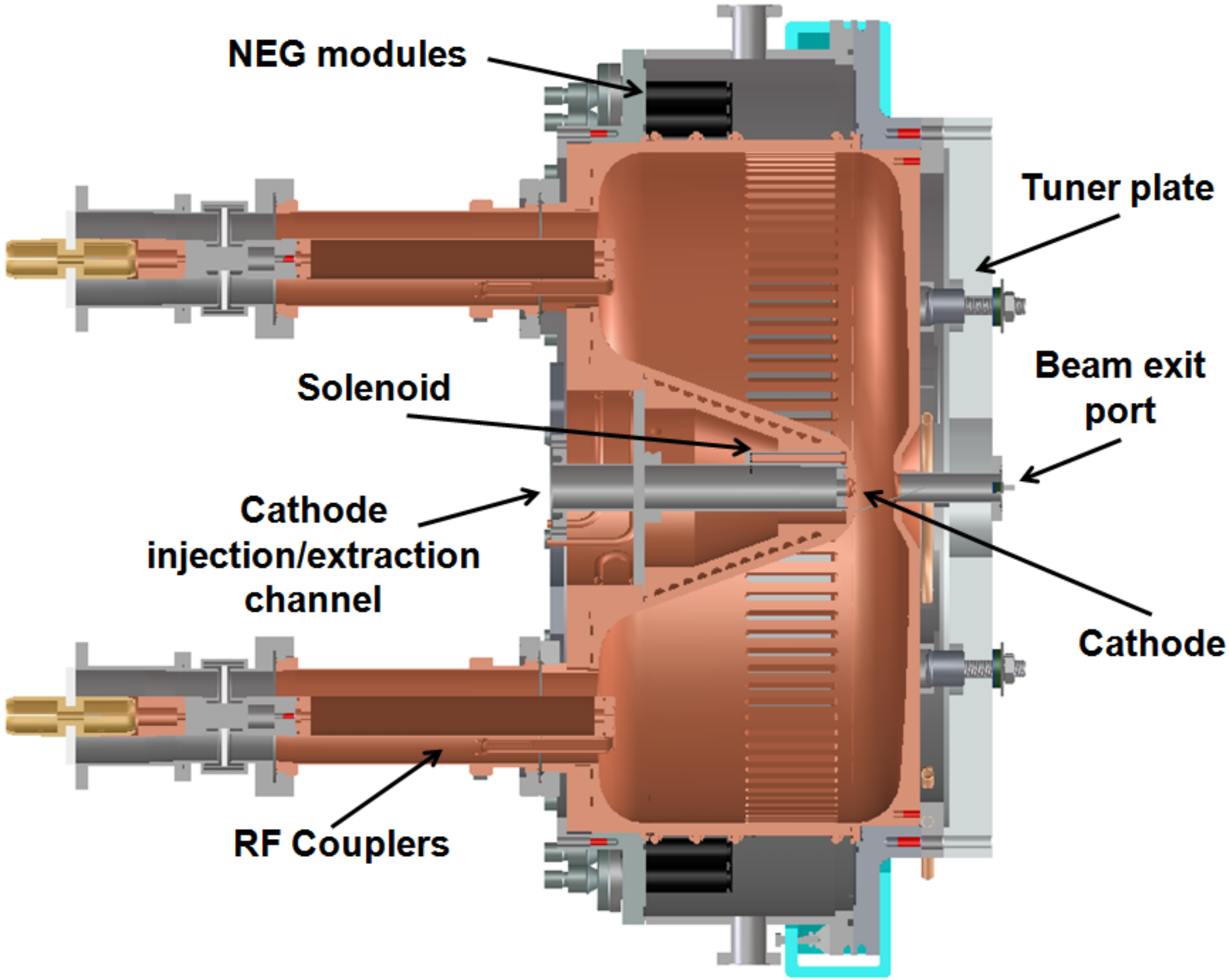
Integrated systems



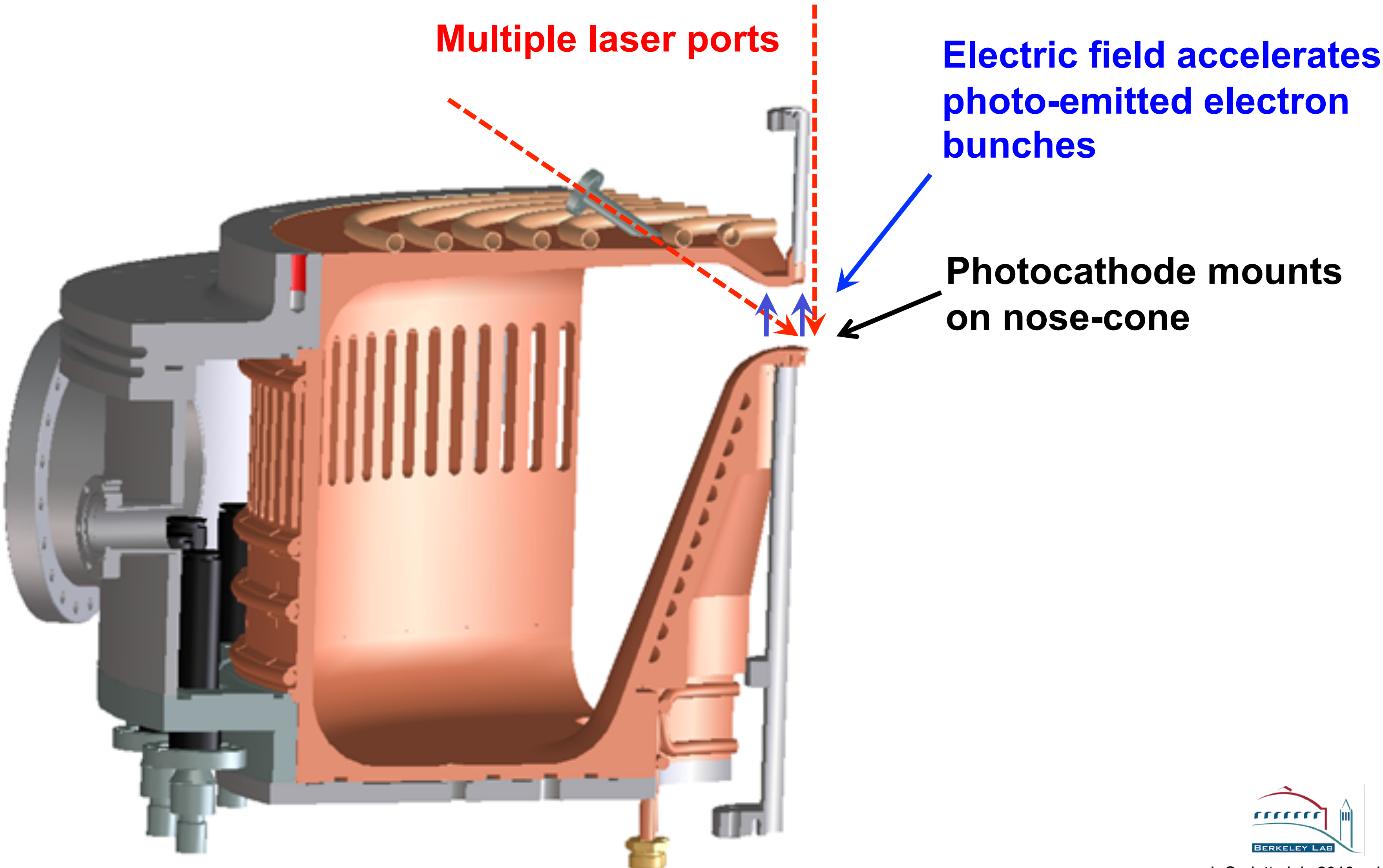
Photocathode laser systems including pulse shaping



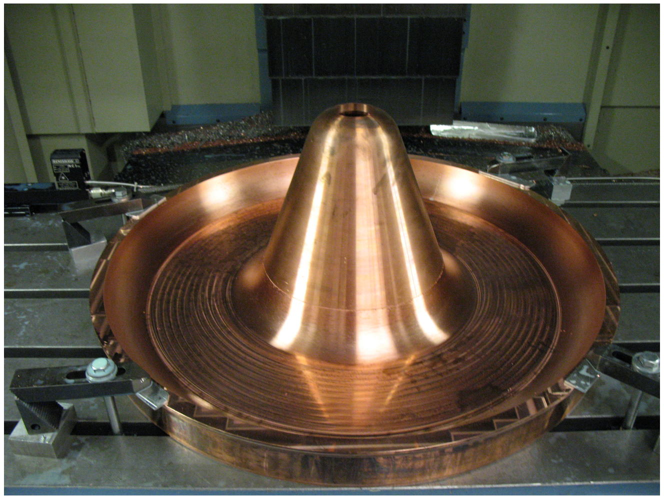
A High Rep-rate VHF Cavity Electron Gun

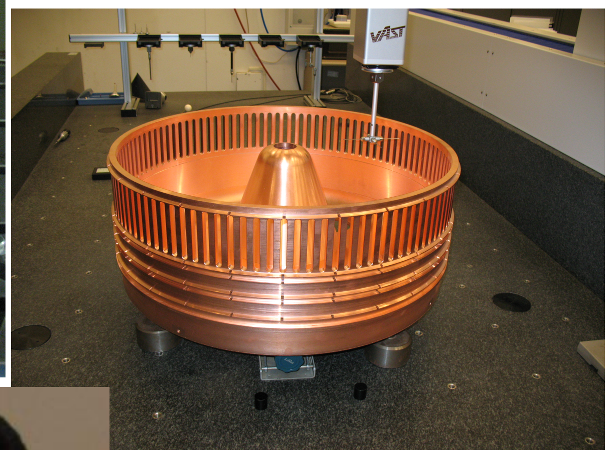


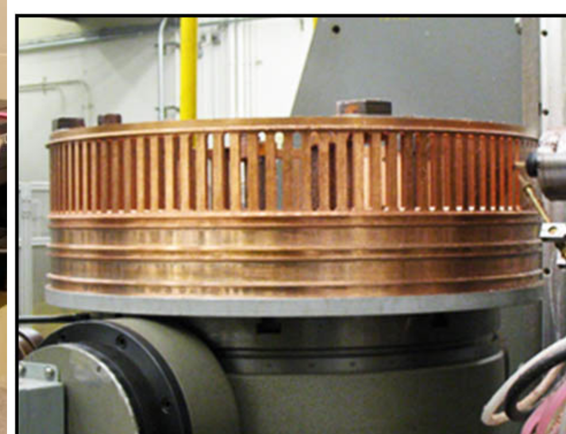
A High Rep-rate VHF Cavity Electron Gun



VHF Gun Cavity Fabrication







High Brightness Photocathodes

Reduce emittance

FEL amplification needs very small emittance, e

$$\varepsilon < \frac{\text{FEL wavelength}}{4\pi}$$

Acceleration to high energy reduces geometric emittance

$$\varepsilon \propto \frac{1}{\text{electron energy}}$$

Smaller initial emittance means

smaller accelerators for fixed wavelength

- *lower cost*

shorter wavelength for fixed accelerator

- *wider capabilities*

Increase efficiency

Metal: QE = 5×10^{-5}, 1 MHz, 4.65 eV, 5% IR-UV

- kW of IR needed, psec pulses
- robust, fast emission

Semiconductor: QE = 5×10^{-2}, IR

- ~W of IR needed
- fragile, slow emission, current limited

Higher efficiency means

smaller lasers for fixed repetition rate

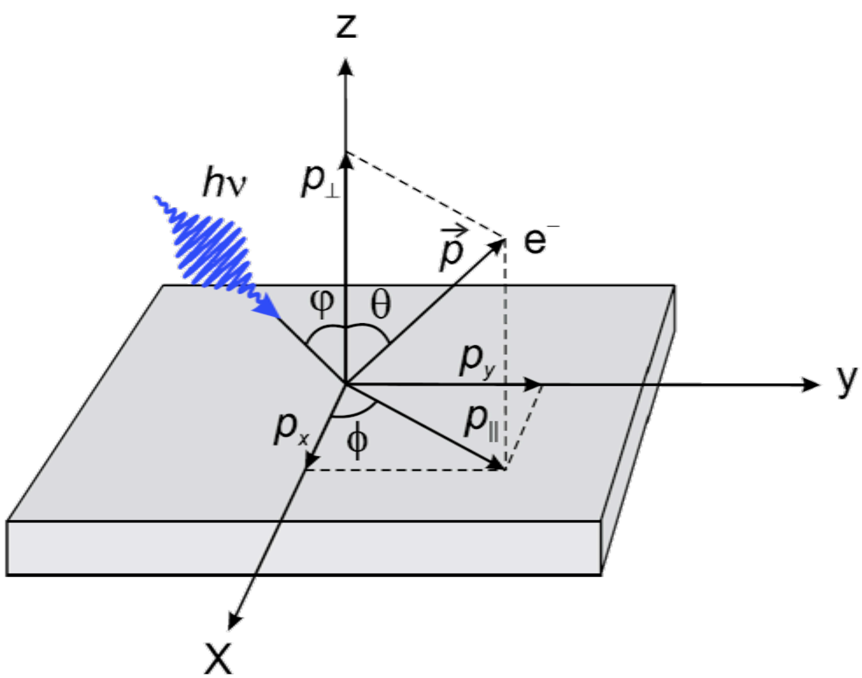
- *lower cost*

higher repetition rate for fixed laser power

- *increased capabilities*

Characterizing Photocathodes

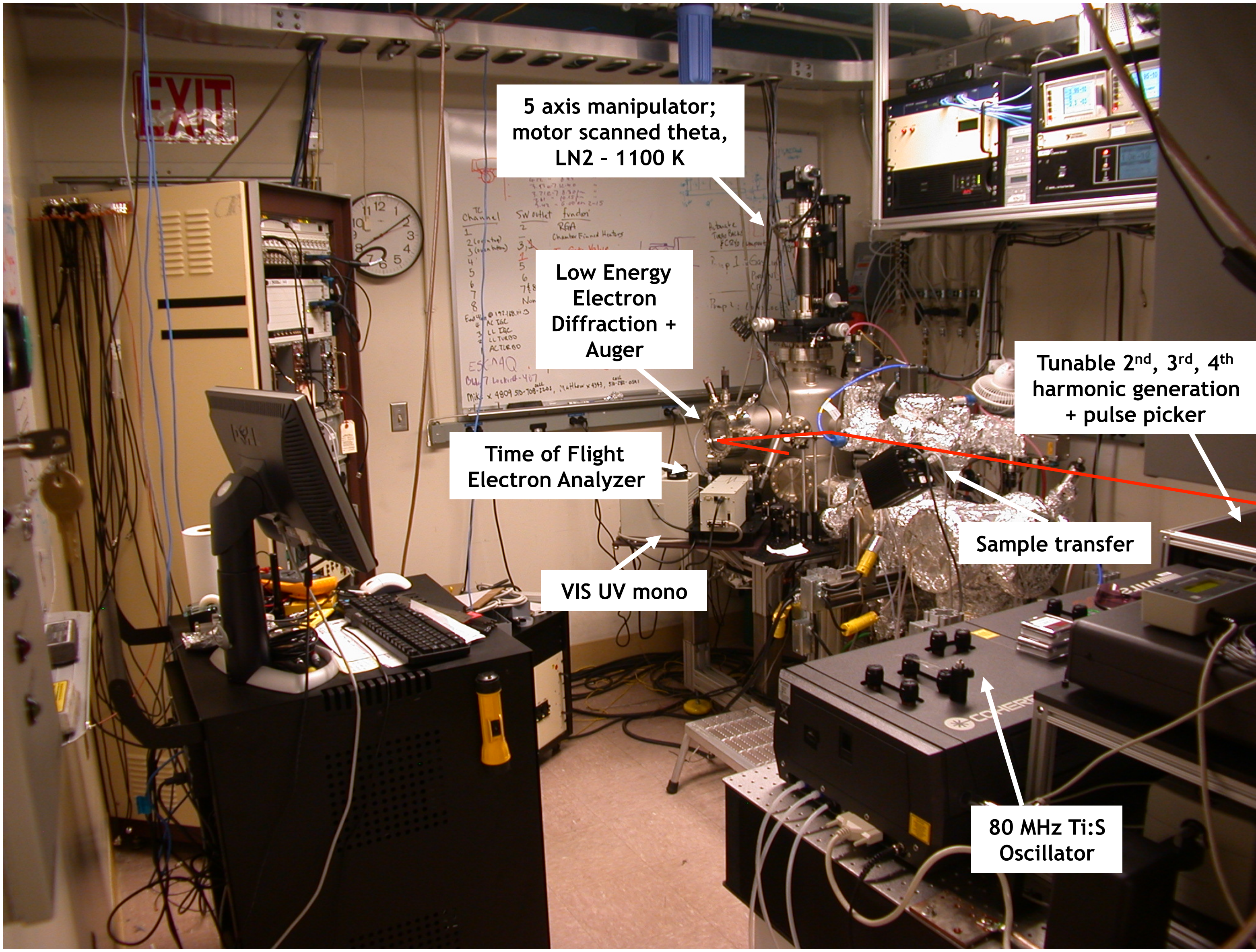
Employ surface science and materials science expertise at the ALS



- **Full measurement of momentum distribution and yield as function of**
  - **Polarization**
  - **Photon energy (2–6 eV)**
  - **Photon incidence angle**
  - **Surface preparation**

- **Techniques**
  - **Ultra-low energy angle resolved electron spectroscopy**
    - **Kinetic energies 0–1eV**
  - **Angle resolved electron yield**

Photocathodes Lab (one of two)



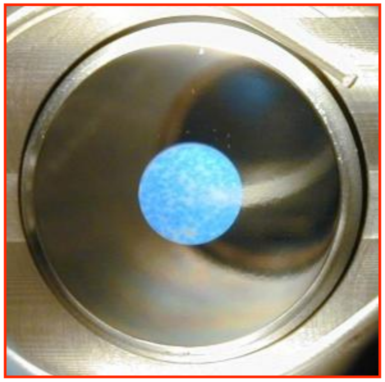
Photocathode Materials

Alkali Antimonides eg. $SbNa_2KCs$

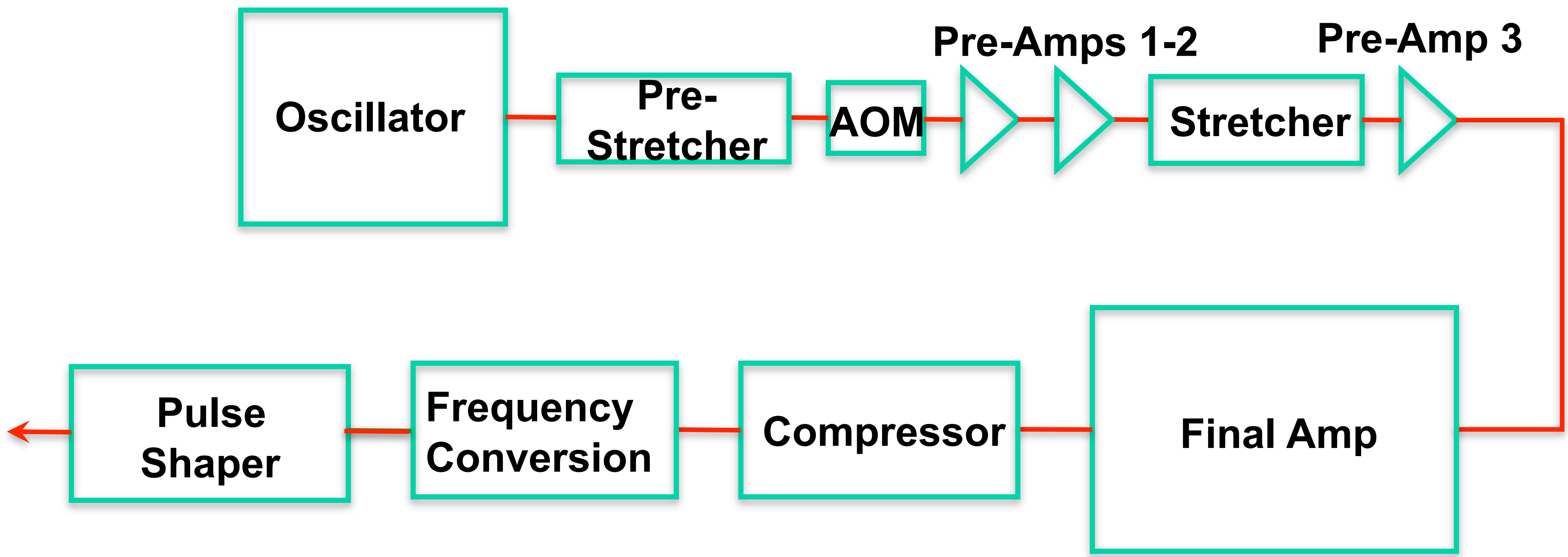
- Fast
- Reactive; requires UHV ~ 1e-10 mBar pressure
- High QE (typ. 10%)
- No pulse charge saturation
- Requires green light (efficient conversion from IR)
- nC, 1 MHz….40 mW of IR required (laser oscillator)
- Unproven at high rep rate and high average current

Cs_2Te (used at FLASH for example)

- Fast
- Relatively robust and un-reactive
  - Can be used in a high gradient rf gun
- High QE; typ. 10%
- No pulse charge saturation
- Requires UV (eg. 3rd harm. of Ti:Sapphire: 5% conversion effic.)
- For 1 nC - 1 MHz reprate, ~ 1 W 1060nm required
- Unproven at high rep rate and high average current



Photocathode Laser (1)



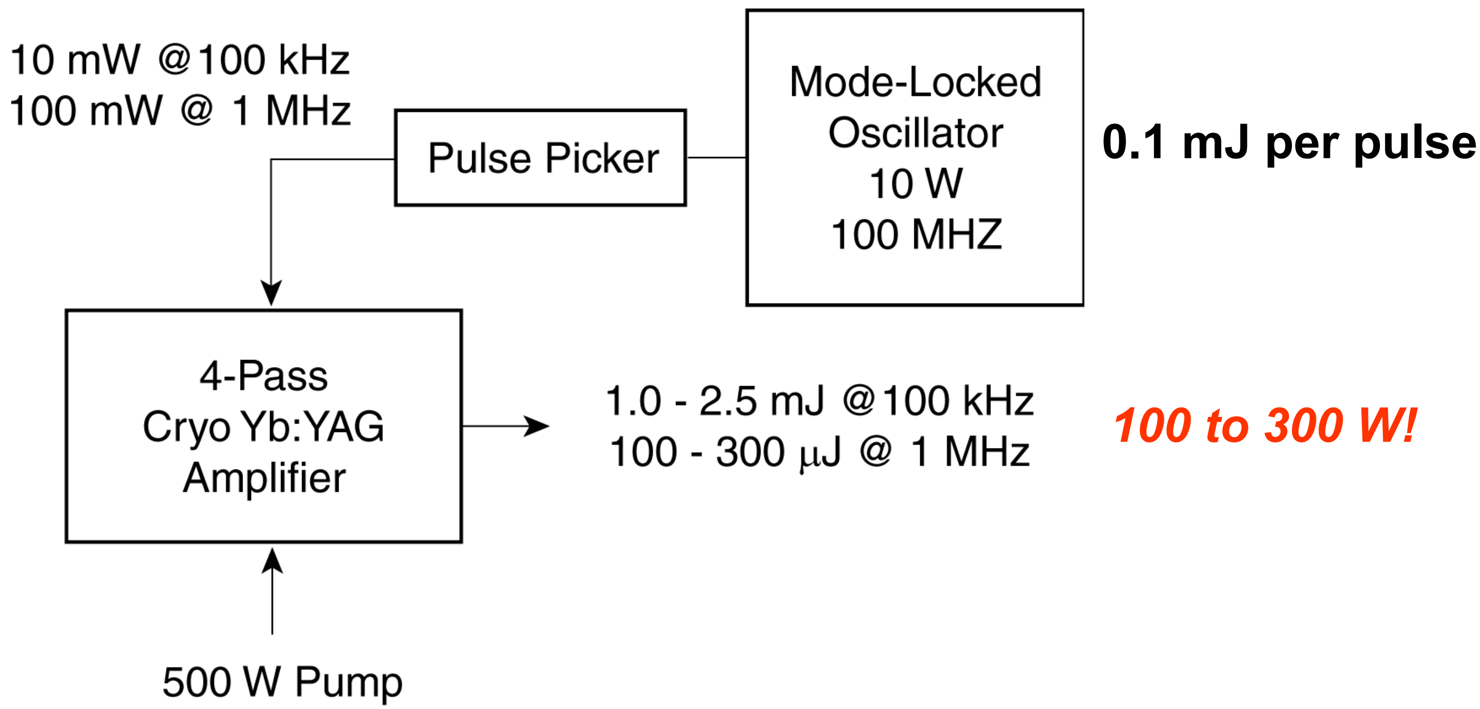
Lawrence Livermore National Laboratory

Built by LLNL

System will deliver:
1 MHz
1 mJ @ 1064 nm (1 W)
~0.4 mJ @ 532 nm (0.4 W)
~1 ps FWHM

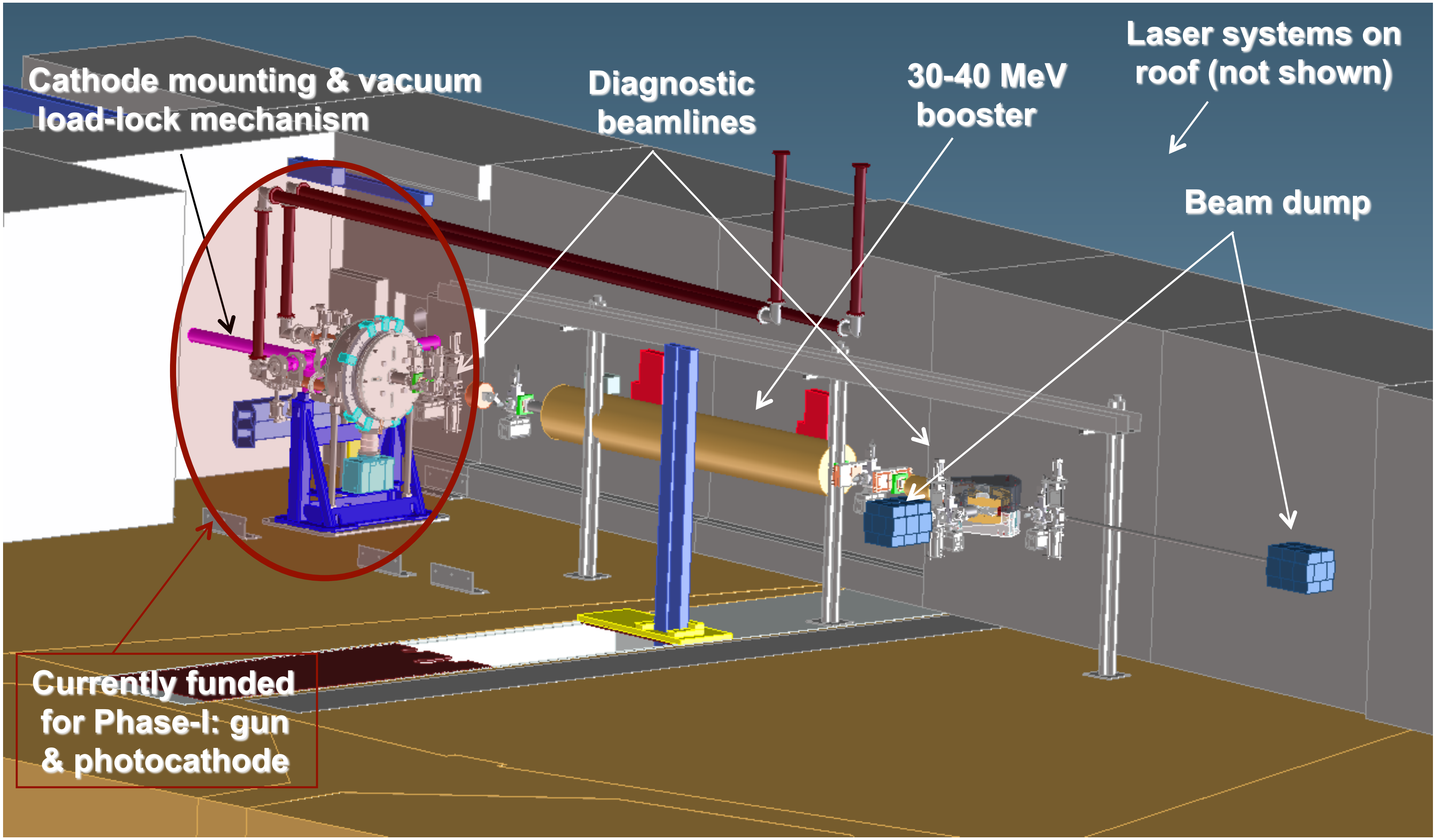
Photocathode Laser (2)

Built by Q-Peak and MIT-LL

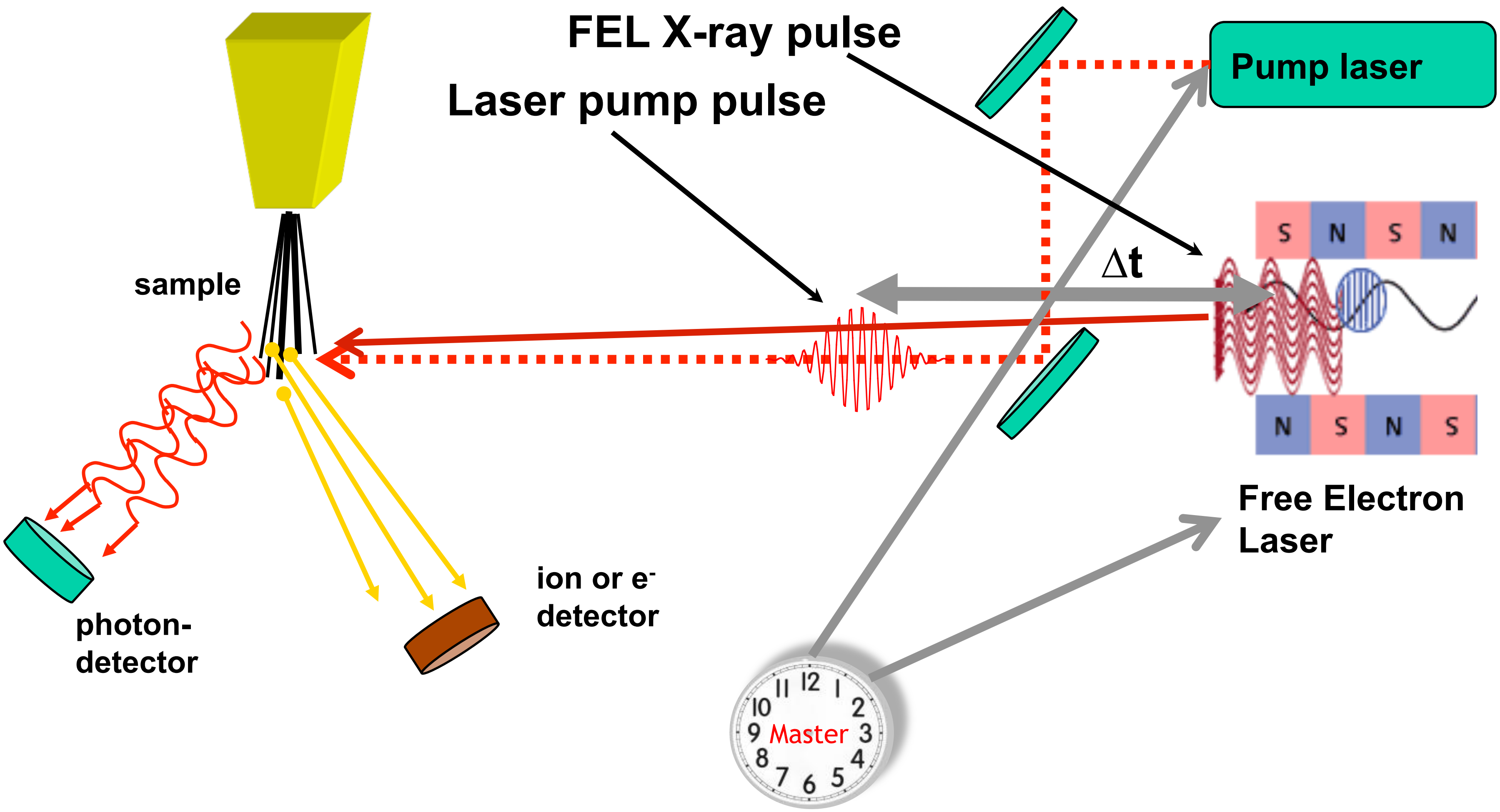


- **Passively mode-locked cryo Yb:YAG laser**
- **Use a pulse picker to reduce the repetition rate to as low as 100 kHz**
- **Amplify the resulting pulse train in a 4-pass cryo Yb:YAG laser**

APEX
Advanced Photoinjector EXperiment

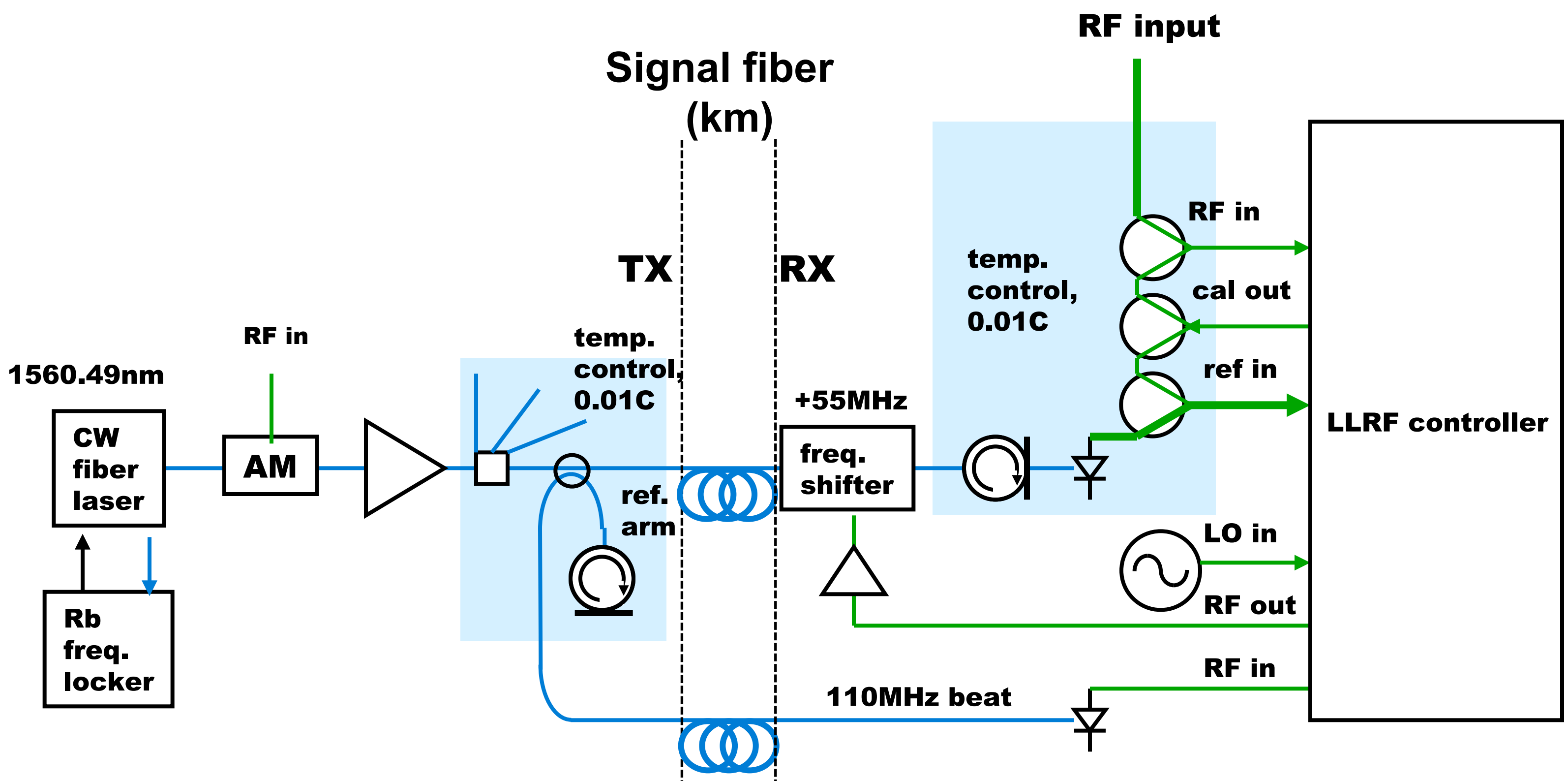


X-ray Pump–Probe Experiments Require Precision Timing & Synchronization



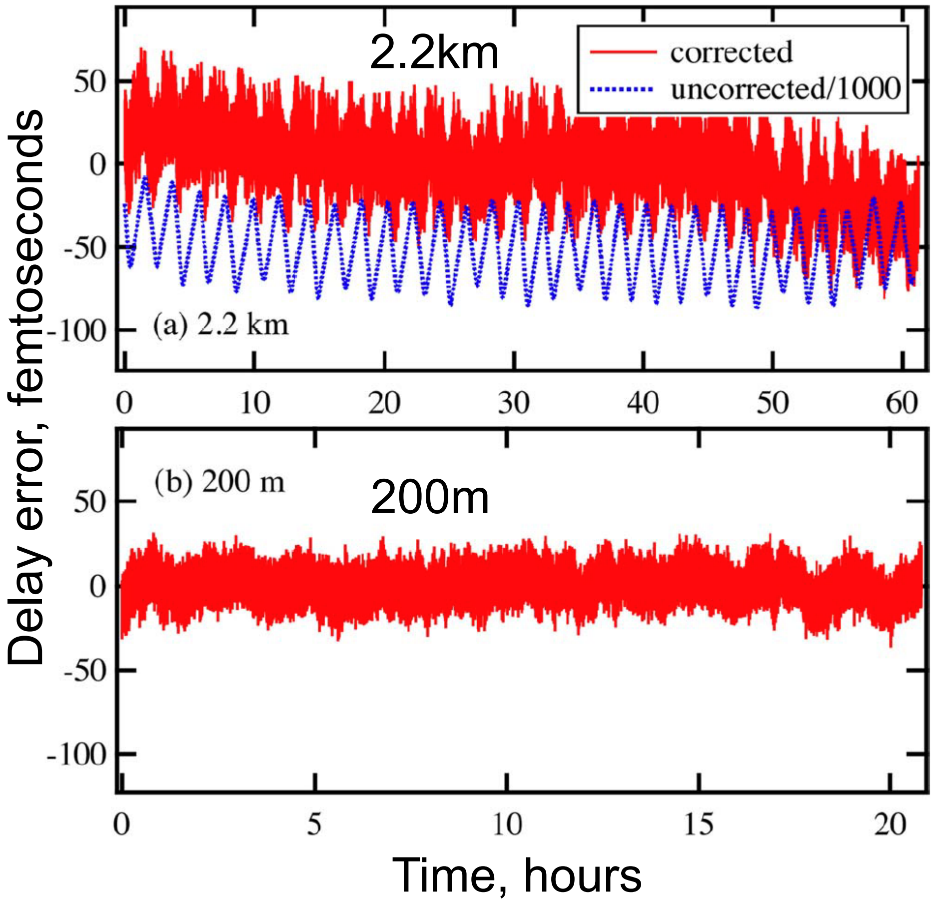
- Ultrafast laser pulse "pumps" a process in the sample
- Ultrafast x-ray pulse "probes" the sample after time Δt
- By varying the time Δt, one can make a "movie" of the dynamics in a sample.
- Synchronism is achieved by locking the x-rays and laser to a common clock.

Timing & Synchronization System

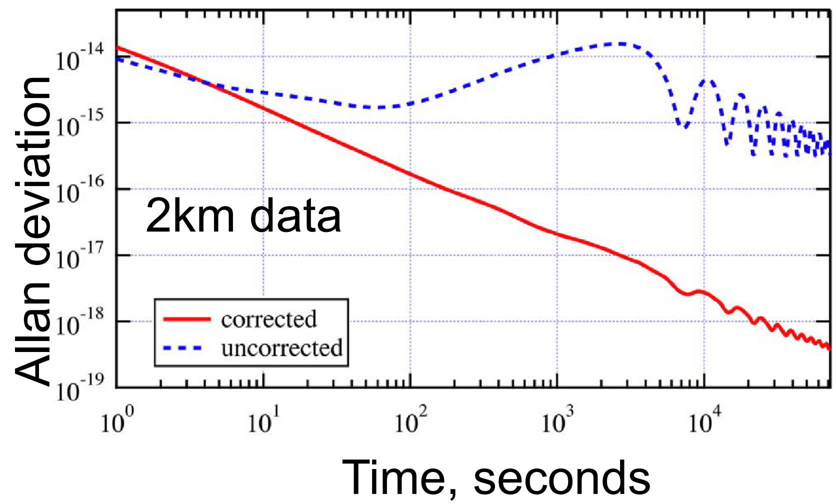


- Changes in line length are sensed by interferometer, beat signal sent to receiver (55 MHz)
- Receiver applies phase shift to frequency shifter RF, stabilizing optical phase at end
- Optical phase correction is used to calculate RF phase shift
- Thermal drift of beat fiber delay is ~1ns, becomes 0.5fs of optical phase error on main
- CW laser is absolutely stabilized
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

Timing & Synchronization Systems Results



- **1kHz bandwidth**
- **For 2.2km, 19fs RMS over 60 hours**
- **For 200m, 8.4fs RMS over 20 hours**
- **2-hour variation is room temperature**

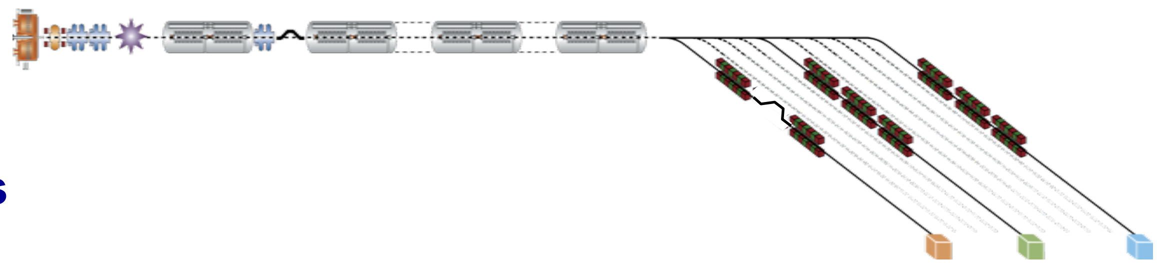


LBNL systems implemented at LCLS

NGLS Studies at LBNL

Design studies for a future FEL facility

- **Coherent soft x-ray laser**
- **10 eV - 1 keV range**
  - **harmonics to 5 keV**
- **Seeded by optical lasers**
- **Multiple, simultaneous beams**
  - **with different properties**
- **Time-bandwidth limited pulses**
  - **Ultrashort (~250 attoseconds)**
  - **Narrow bandwidth (meV)**
- **High peak power - for nonlinear optics (~ 1 GW)**
- **Control of peak power - 10–1000 MW to minimize sample damage**
- **High average power - for low scattering rate experiments (~ 1–10+ W)**
- **High repetition rate - for good S/N (~100 kHz–MHz+ for some beamlines)**
- **Capable of serving large number of users (~ 2000 users/year)**

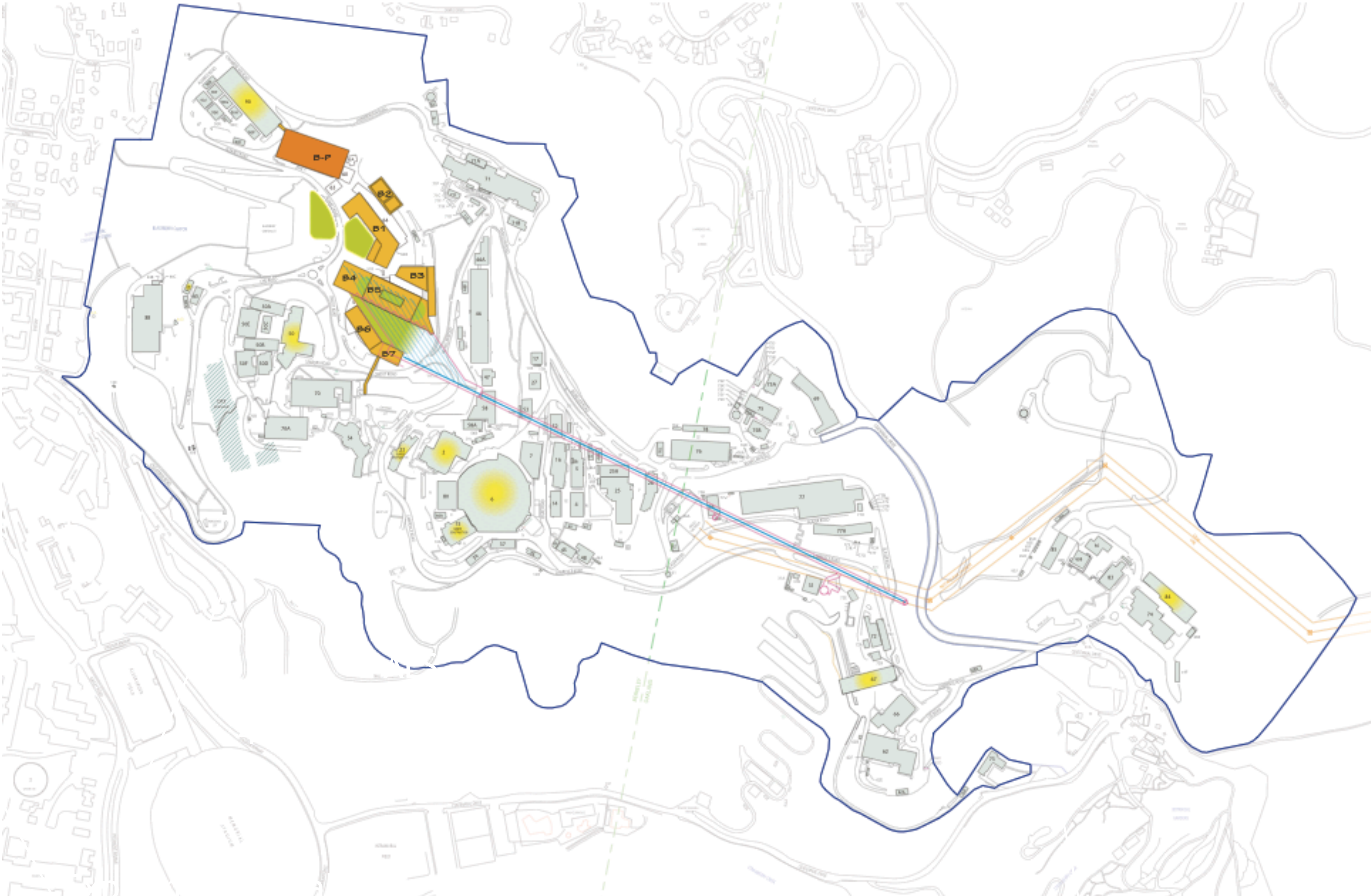


Thanks to an Excellent Team
Contributions From Many Divisions Within LBNL

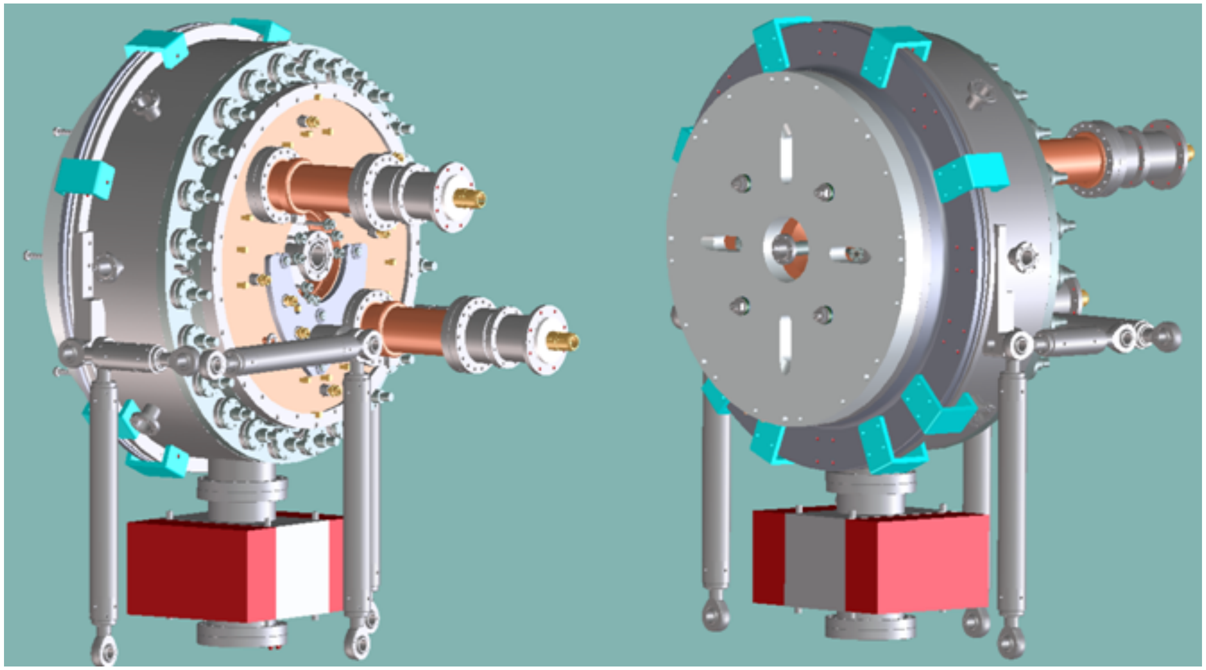
Ken Baptiste
Walter Barry
Ali Belkacem
John Byrd
Andrew Charman
John Corlett
Woody Delp
Peter Denes
Rick Donahue
Larry Doolittle
Roger Falcone
Bill Fawley
Jun Feng
Daniele Filippetto
Stefan Finsterle
Jim Floyd
Steve Gourlay
Mike Greaves
Joe Harkins
Zahid Hussein
Preston Jordan
Janos Kirz
Eugene Kur
Slawomir Kwiatkowski
Steve Leone
Derun Li
Steve Lidia

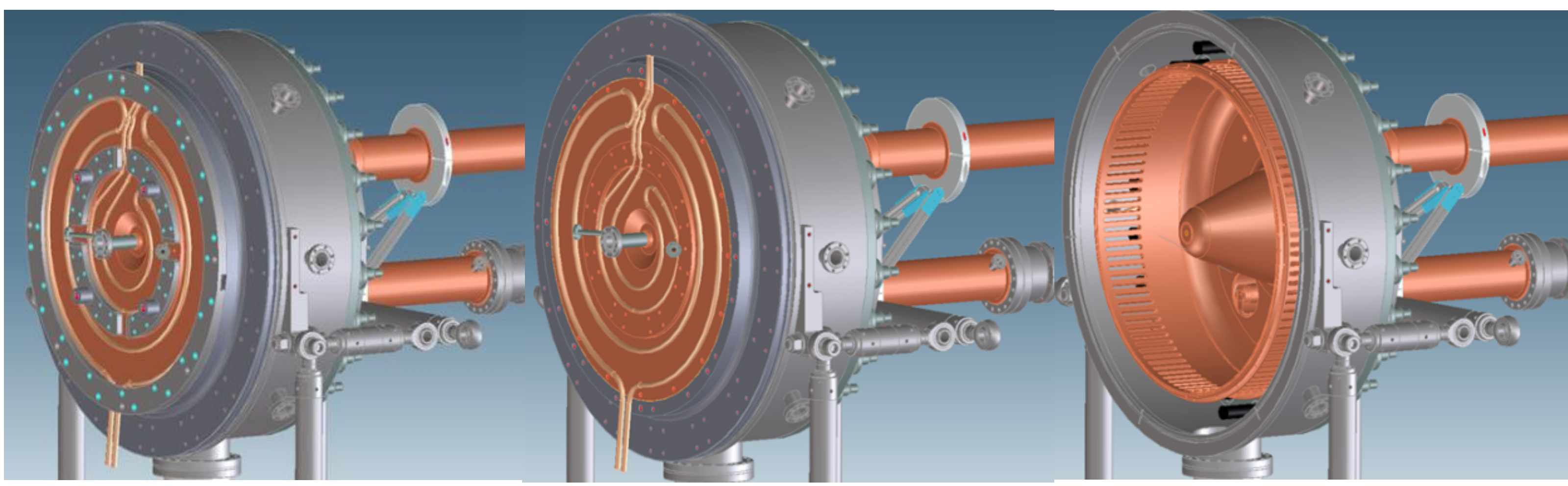
Tak Pui Lou
Bill McCurdy
Pat Oddone
Howard Padmore
Christos Papadopoulos
Gregg Penn
Paul Preuss
Ji Qiang
Alex Ratti
Matthias Reinsch
David Robin
Kem Robinson
Glenna Rogers
Fernando Sannibale
Richard Sextro
Bob Schoenlein
John Staples
Christoph Steier
Theodore Vecchione
Will Waldron
Weishi Wan
Russell Wells
Russell Wilcox
Jonathan Wurtele
Lingyun Yang (BNL)
Sasha Zholents (ANL)
Max Zolotorev

A NGLS at LBNL

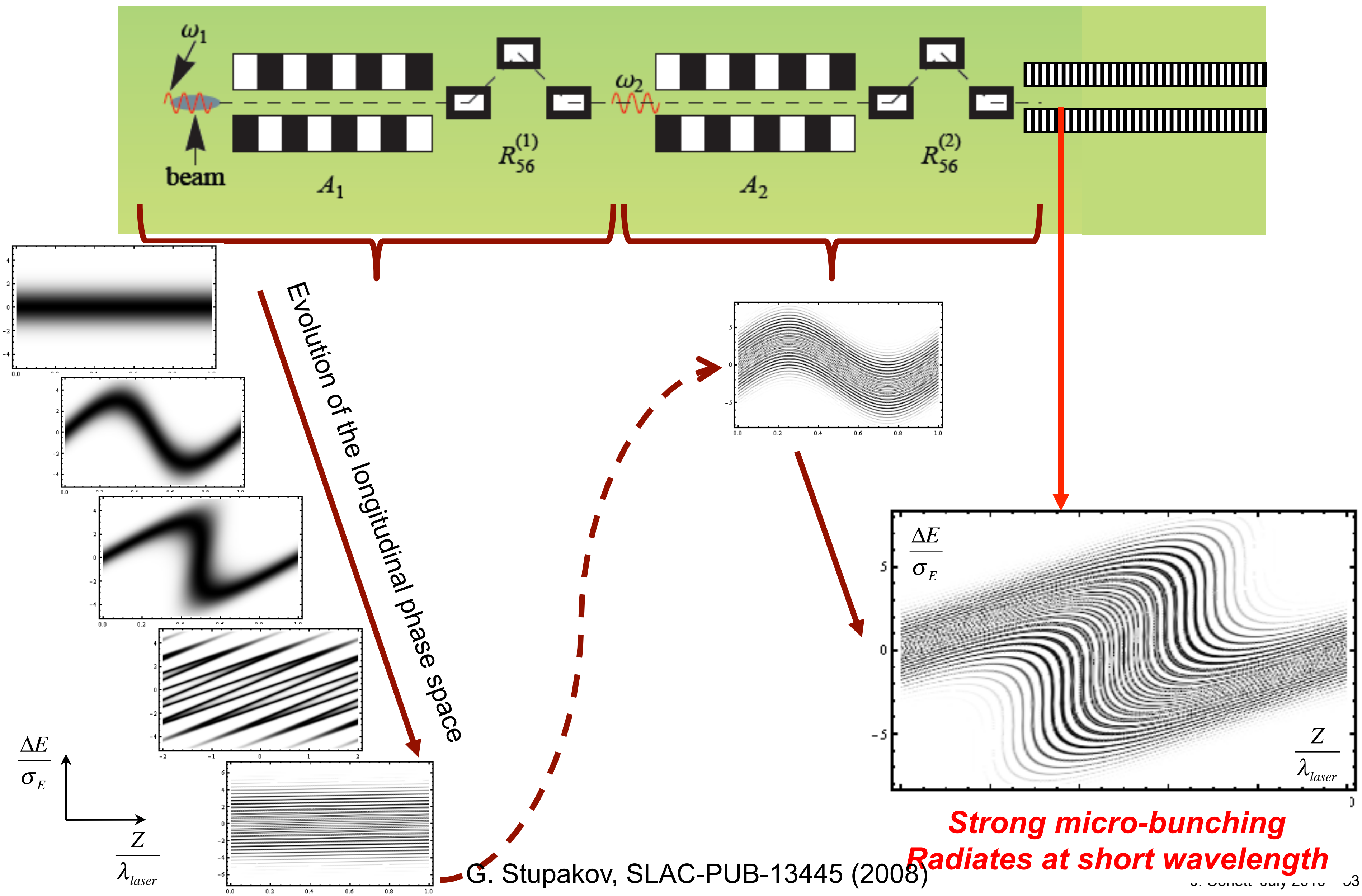


VHF Gun CAD Model





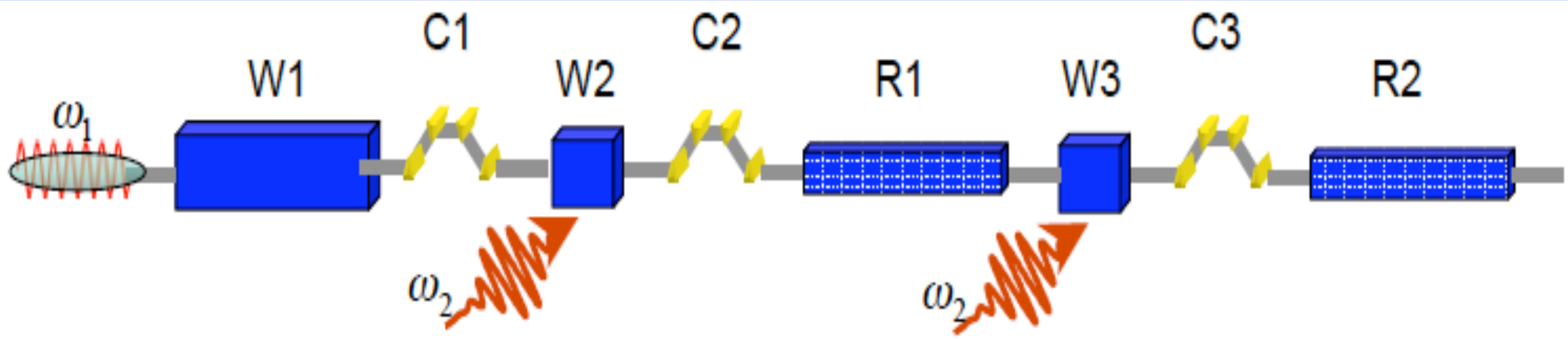
Echo Enabled Harmonic Generation

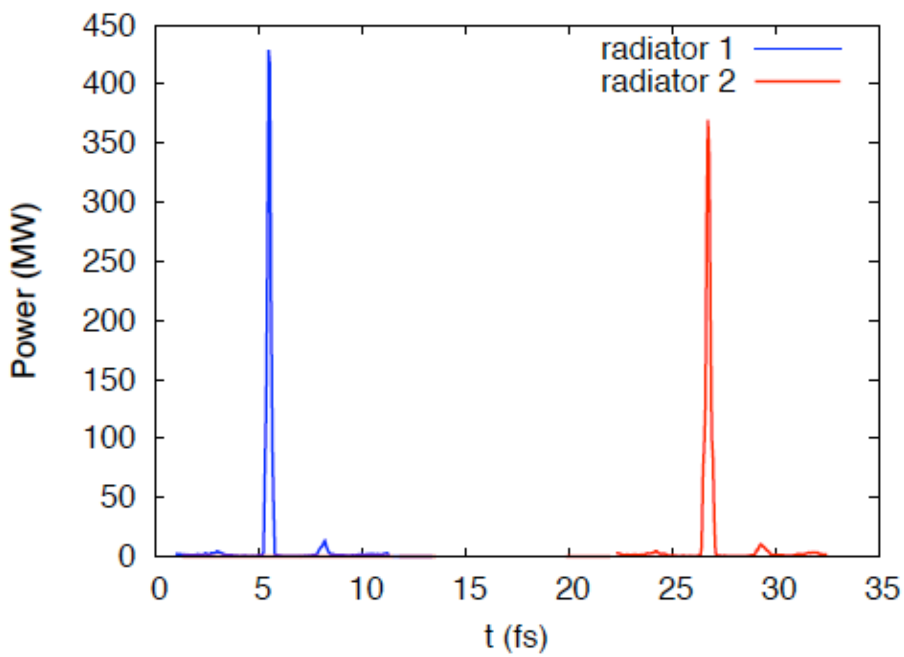


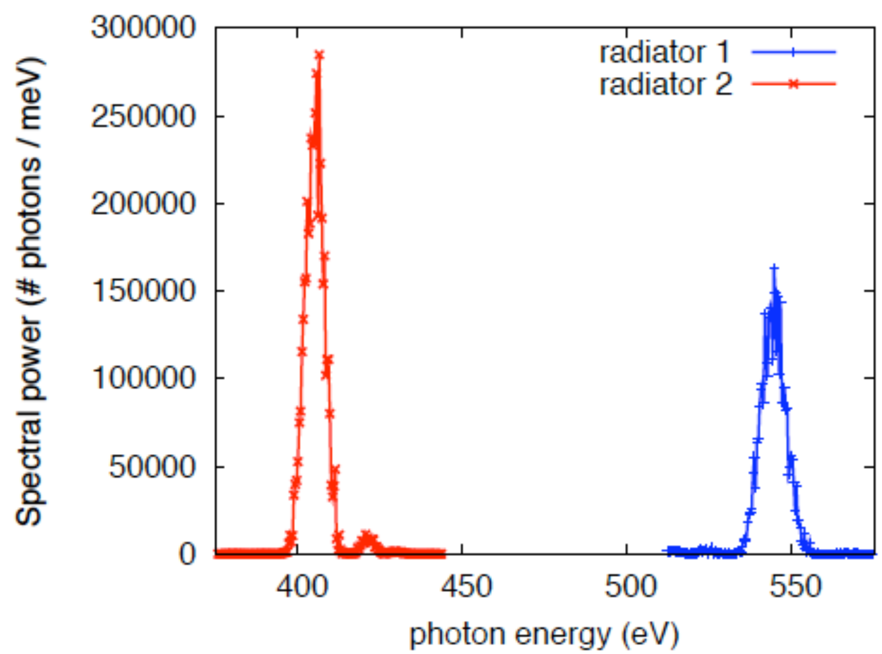
G. Stupakov, SLAC-PUB-13445 (2008)

Strong micro-bunching
Radiates at short wavelength

Two-color Ultrafast Pulses with Time Delay







~250 as pulses with variable wavelength and variable delay

A. Zholents, G. Penn, "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy", NIM–A, **612**, 2, 2010